FOOD SECURITY, POPULATION GROWTH AND CLIMATE CHANGE: IMPLICATIONS FOR FORESTLAND CONVERSION AND GLOBAL FOOD PRICES

Roxana Juliá
Global Liberal Studies
College of Arts and Science, New York University
726 Broadway, New York, NY 10003
E-mail: rj34@nyu.edu

Faye Duchin
Department of Economics, Rensselaer Polytechnic Institute
110 8th St., Troy, NY 12180, USA
E-mail: duchin@rpi.edu

May 10, 2012

Selected paper prepared for presentation at the International Society for Ecological Economics Biannual Meeting, Rio de Janeiro, Brazil, June 16-19 2012.

Abstract. The overall objective of this research is to provide an understanding of the likely stress that future global food demand may impose on the world's forestlands and on the price of food. To do so, we test a set of combined scenarios of the future, with and without climate change, and allowing and not allowing for forestland conversions to take place. We test the scenarios with an extension of the World Trade Model with Climate-Sensitive Land (WTMCL) presented in Juliá and Duchin (2007), which represents a comprehensive integration of a generalized system of specialization based on comparative advantage with an approach that quantifies climatic responses of agricultural and forest resources under alternative climates, and allow for trade adaptations to take place. We emphasize the analysis on the feasibility (or not) of a year 2100 agricultural demand fulfillment, and on the likely direction and magnitude of forestland conversions and price changes that may result after trade adaptations take place. We find that the projected demand (driven by population growth) cannot be fulfilled in a world with climate change unless significant levels of forestland conversions into agricultural land take place. Conversion of forestland into croplands, in particular, emerged as a powerful mechanism not only to attain future agricultural demands but also to avoid a sharp increase of global agricultural commodity prices. This finding raises concerns given the roles that ecosystem services provided by forests represent for the maintenance of a stable climate and environment.

1. Introduction

Most studies of the impacts of climate change on agriculture and the role of trade as an adaptive mechanism predict that global food sufficiency will not be jeopardized for the next century or so (Darwin et al. 1995; Randhir and Hertel 2000; Reilly et al. 1994; Rosenzweig et al. 1993; Tsigas et al. 1996; Winters et al. 1999). Their conclusions argue that a well-functioning system of trade, responsive to price signals, should help shift commodity production to regions where comparative advantage for agricultural production improve, compensating for potential losses in other regions of the world. Furthermore, they predicted that prices of agricultural commodities could even decrease in response to such adjustments. Juliá and Duchin (2007), however, found that while trade could make it possible to satisfy world demand for agricultural crops under the changed climatic conditions, trade adaptations to climate change implied an increase in prices of agricultural commodities, and a decrease in access to food in some regions of the world. Furthermore, they pointed out the stress that changing climatic conditions imposed in the productivity of (scarce) agricultural land, particularly croplands.

Juliá and Duchin's methodology differed from previous studies: their model made a direct association between changes in productivity – affected by climatic conditions - and associated cost structures in any region, on the one hand, and global patterns of production and trade and regional prices, on the other. Their claim was that such approach was an improvement in terms of tracking changes in regional comparative advantage - the rationale for viewing international trade as a means for adapting to climate change.[i] Many assumptions aimed at simplifying their analysis and isolating the effect of climate change on agricultural systems and the likely adjustments that can be expected in a global system of trade, however, limited the applicability of their findings. One of such assumptions was that demand for food remained at the level of their benchmark scenario (a 1990 scenario without climate change), a restricting assumption given that population growth and higher per capita consumption among communities with growing incomes (particularly in Asia) will certainly increase the demand for food in the years ahead. A study conducted by the Food and Agriculture Organization of the United Nations projects, for example, that demand for cereals will increase by 70% by 2050, and will double in many low-income countries (FAO, 2006).

Another limitation of Juliá and Duchin's study is that they did not allow for forestland conversions to agricultural land. Rates of deforestation – particularly in tropical forests – may increase significantly in the twenty-first century, driven mostly by population growth and agricultural trade. Allowing for such conversions of land may also arise as a mechanism of adaptation to the impacts of climate change, as climatically suitable land, currently under forests, may be converted into agricultural land to compensate for land being lost to (agriculturally unfavorable) changes in climate in some regions of the world.

In this study we extend Juliá and Duchin's study and evaluate whether the reallocation of agricultural specialization in response to climate change will function in a way the fulfillment of agricultural commodities demand by the year 2100, driven by population growth, will not be jeopardized. We contrast combined scenarios of the future, with and without climate change, and allowing and not allowing for forestland conversions. We emphasize the analysis on the feasibility (or not) of demand fulfillment, and the likely direction and magnitude of forestland conversions that result from the simulations. We also emphasize our analysis in the likely direction and magnitude of change in agricultural commodity prices that may result from trade adjustment needed to satisfy demand needs. The evaluation and prediction of potential food price changes is an indispensable component of predictions of potential food crises as they have a direct impact in food accessibility, particularly in low-income regions, where a high proportion of the household income is spent in food purchases.

Our results predict that future population growth-driven agricultural demands are not attainable if climate change impacts the system as predicted by mayor General Circulation Models, and if forestland areas are preserved intact. However, allowing for forestland conversion – and expanding agriculture to regions that "gain" productivity due to the new climatic conditions not only allowed the system to fulfill future agricultural demand, but allowed to do so a relatively small increases – and even decreases for some crop – in world prices. Forestland conversion emerged as a powerful incentive to overcome the pressure that population growth and climate change may impose on future generations. This is an area of great concern, given the many ecosystem services provided by forests in terms of maintaining a stable climate and sustainable livelihoods.

The next section presents the modeling framework used for the analysis, and modifications and extensions made from Juliá and Duchin's original aggregation and assumptions. Section 3 describes the scenarios tested using the aforementioned model. Section 4 presents the results of the scenario runs, and the final section concludes with a summary and discussion, along with the identification of priorities for further work.

2. Methodology

The analysis is carried with the modeling framework introduced by Juliá and Duchin (2007), the World Trade Model with Climate-Sensitive Land (WTMCL), which takes the form of a linear optimization problem that integrates a fully generalized system of trade for *m* regions, *n* goods and *k* factors based on comparative advantage (as presented by Duchin, 2005) with the spatial analogues approach (Darwin et al., 1995), that quantifies climatic responses of land resources under alternative climates.

In the WTMCL, the values of the economic (endogenous) variables – output, trade flows, factor scarcity rents and world prices – are determined on the basis of simultaneous consideration comparative advantage drivers: consumption requirements, technologies, factor endowments and pre-trade factor prices, which are empirically determined and enter the model as exogenous data. The model minimizes factor costs subject to regional consumption demand and factor endowments; the gains from trade arise from the ability of regions and of the world as a whole to sustain given world consumption at minimum factor cost.

Darwin et al.'s approach is based on the insight that there is a systematic relationship between differences in regional climates and agricultural productivities for specific uses of land of otherwise comparable qualities. They classified land resources into six classes based on their respective length of growing season (LGS) – the longest continuous period in a year that soil temperature and moisture conditions support plant growth. – a variable that highly correlates with crop suitability and productivity. A region's land-class endowment for each potential land-use type defines in the model a region's production potential – and together with other economic variables, the region's comparative advantage for regional specialization on particular crops. Table 1 presents the main characteristics of the six land-class categories and their respective crop suitability.

[Table 1]

According to Darwin et al.'s rationale, climate change alters the regions' relative mix of climatically-defined land endowments and with it the patterns of regional specialization and exchange. Regions adjust by changing the mix of agricultural products and the area devoted to agriculture – two of the major mechanisms of adaptation highlighted in the literature. The strength of this formulation is that it makes a direct association between changes in productivity and associated cost structures in any region on the one hand, and global patterns of production and trade and regional prices, on the other, allowing for the endogenous determination of the optimal pattern of specialization and world prices associated with assumptions about changes in climate. A complete specification of the WTMCL is included in Appendix A.

2.1 Prices in the WTMCL

Commodity prices and factor scarcity rents in the WTMCL respond to changes in assumptions about the exogenous variables, including the relative mix of climatically-defined land resources, and the direction and magnitude of these responses constitute the solution of the dual to the primal linear program.

World prices decompose into payments to intermediate inputs, payments to factor inputs at initial factor prices, scarcity rents and benefit-of-trade rents (See Appendix A, eq. 6). The last component (benefit-of-trade rents, α_i) represent the dual prices associated with eq. 5, and convey the extra payments to regions for which the value of exports is greater than imports (both valued at pre-trade prices). Eq. 6 assures that prices are high enough to accommodate this rent (Duchin, 2004). Changes in world prices reflect then changes in payments to intermediate inputs and factors of production, including factor scarcity rents associated with the adjustments (see Appendix A, Eq. 6). There is only one world trade price for each traded commodity group. However, for the agricultural commodities that use land as a resource, those decompose according to the land-class type where the commodity is produced. This is an important attribute because it means that differing productivities of different land-classes used in producing regions define scarcity rents and so influence the world price of the commodity. The price slacks in eq. 6 take a value of zero only when the commodity output in a specific region and land-class type (for the agricultural commodities) takes a value different from zero. The price slacks in eq. 6 represent the reduced cost for the commodity in a particular region, and reflect the amount by which the regions would have to reduce their production cost (i.e., gain comparative advantage) so as to actually specialize in the production of a particular crop. If a region produces the commodity in question, the price slack is equal to zero.

2.2 Model Aggregation and Data Sources

The model was implemented for 10 regions comprising the world economy: North America, the European Community (as it was in 1990), Other Europe, the former Soviet Union, Japan, Eastern Asia (China, Hong Kong, Taiwan and South Korea, with China the dominant economy), Rest of Asia (with India the dominant economy), Latin America, Africa and one region comprising Australia and New Zealand (from now on, Australia).

The commodity aggregation specified for this particular study differs from the one used in Juliá and Duchin's study. It retains the seven non-agricultural sectors (coal, oil, gas, electricity, minerals, manufacturing and services), but in order to increase sensitivity to regional climatic impacts, agriculture is disaggregated into eight (instead of three) categories: rice, wheat, corn, vegetables fruits and nuts, oilseeds, sugar crops, fibers, and other agriculture (a residual category). Agricultural commodities' production and demand are measured in physical units (10 million tons for crops and millions of heads for livestock) with the aim of improving transparency in the link between biophysical and economic impacts of climate change.

Factors of production are labor, capital, and land. Land is classified in three major use categories: cropland, pastureland, and forestland. Each land category is subdivided into six land-class types defined by Darwin *et al.* (1995). Figure x shows the global endowments of each land use/type combination, as reported by Darwin et al.

3. Scenarios

Table 2 presents the climate change scenarios that are used to test the aforementioned hypothesis.

[Table 2]

Population increases for the year 2100 were estimated for each particular region using projections reported by the United Nations, Population Division (UN, 2004); Figure 1 shows the estimated changes. We used these figures to estimate changes in future demand of agricultural commodities, which were assumed to increase proportionally to those. Regional differences in population growth are likely to be significant (predominantly bigger in Africa) as are the projected regional changes in crops and livestock demand that follow those. Figure 2 illustrates the magnitude of these differences for rice and wheat (in 10^4 Metric Tons). The benchmark, 1990 values of demand for each crop category were computed using FAO, Statistical reports for the year 1990. The composition of diets (i.e., the percentage that each agricultural commodity represented in the final consumption vector) remained as in the year 1990. Population increases drove also increases in labor and capital endowments, the proportion of those per region remaining as in the year 1990.

[Figure 1]

[Figure 2]

The three climate change scenarios used to impact the productivity of the system correspond to climatic results obtained for a doubling of atmospheric concentrations of carbon dioxide at the Goddard Institute of Space Studies (GISS), the United Kingdom Meteorological Office (UKMO) and the Geophysical Fluid Dynamics Laboratory (GFDL), respectively. Each climate change scenario affects the suitability of land for agricultural production and is represented in the WTMCL by values of the distribution of climatically defined land endowments – as reported by Darwin et al. - for a given region. Figure 3 illustrates the global changes in land-class endowments that are assumed under each of the scenarios.

[Figure 3]

For all land-use types, and for all scenarios, there is a redistribution of land-classes from the extreme types to middle types. Losses of land-classes of type 1 (see Table 1 for a description) are due to the warming of current boreal, temperate and arctic regions while decreases in type 6 land-classes reflect the shortening of the growing season due to diminishing amounts or deteriorating distribution of rainfall. Current boreal, arctic and high latitude regions (such as Canada and the former Soviet Union)are likely to experience losses of coolest land-classes (type 1); on the other side, soil moisture losses are likely to reduce LGS in many areas of the world; this is the reason for the decrease in land-class type 6 (mostly tropical areas of northern Africa, Asia and Brazil) and increases in type 2 (deserts and semi-desert shrub lands and grasslands) (Darwin et al., 1995). Most of the impacts will take place on forestlands and pasturelands: only 5 % of middle land-class type gains occur in croplands This fact has implications for the capacity of the system to compensate for potential losses in productive areas: 65 % of gains in land-classes of types 3 and 4, especially suitable for grain production, occur in forestlands.

Directional changes in land class types are similar across different climate change scenarios; simulations differ in the magnitude of such changes. Overall, the GFDL scenario anticipates the smaller impacts of climate change on climatically- defined land classes, overall.

To allow for forestland conversions to cropland and pastureland, each land-class combination of forestland was introduced in the factor constraint vector, augmenting cropland and pastureland use possibilities per region and land class (see Appendix A, eq. 4). Factor requirements per unit of forestland available for conversion followed the respective region/land class assignment combination.

4. Results

4.1 Global Scenario Feasibility and Forestland Conversions

Table 3 shows the outcome of all scenario runs. In a world without climate change, projected increases in demand due to population growth did not jeopardize food availability: scenarios A and A1 delivered feasible solutions. Adjustments entailed an increase of 61.4 % in global costs of production (compared to the 1990 benchmark scenario) without forestland conversion to croplands r pasturelands and of 58.1 % when forestland conversion to cropland was allowed.

[Table 3]

When the impacts of climate were introduced in the system (via a change in the relative endowment of climatically-defined land types) the fulfillment of the projected 2100 global demand of agricultural commodities turned unfeasible for all climate change scenarios. Allowing for forestland conversions to croplands turned the solutions feasible, with global costs similar to the ones incurred in the 2100 scenario with no climate change and land conversions. These results are important because they imply that climate change is a serious threat to food demand sufficiency – as it compounds the pressure of population growth.

The global magnitude of forestland conversions required for the world to satisfy food demand is presented in Table 4. The impacts of climate change resulted in an additional 20, 18 and 14 percent of land for the B1, C1 and D1 scenarios respectively (see table 2). This result is important too because it implies that climate change compounds the pressure that population growth imposes in current and future deforestation rates. The majority of the forestland converted was used as croplands; only 1 percent or less of the total land converted was used as pastureland in all scenarios (see Table 4). Figure 4 shows the relative size of forestland conversions to croplands by region, after the model scenarios B1, C1 and D1 runs.

[Table 4]

[Figure 4]

Latin America, North America and Rest of Asia showed the highest rates of conversions, in particular Latin America, which accounted for about ¾ of all forestland converted for all climate change scenarios.

Allowing (or restricting) forestland conversions are likely to have an important impact on the regions' comparative advantage gains (or losses) for crop production. Figure 5 illustrates this prediction for the case of scenarios A and A1, that is, a scenario with population growth and no climate change, not allowing and allowing for forestland conversions, respectively: Latin America increased its allocated production of most crops (with the exception of oilseeds), while the European community, which show very little expansion of agriculture into forestlands lost comparative advantage – and specialization - for the production of rice, wheat and vegetable, fruits and nuts. While such comparisons could not be made for the climate change scenarios due to their infeasibility when no forestland conversion were allowed, the effect may still hold valid, and may even be compounded by the impacts of climate change given the results presented above.

[Figure 5]

The feasibility of the climate change scenarios entailed many reallocations of production across land-class types and regions, resulting in different patterns of regional specialization and trade. Figure 6 illustrates percentage changes (from the A1 scenario) in crop production quantities for the three regions that showed the more sensitive responses: Latin America, Australia, and Rest of Asia.

[Figure 6]

Reallocations took place for livestock production alike. Figure 7 shows specialization changes that allowing for forestland conversions generated for model scenarios without climate change (A and A1) and Figure 8 shows changes from scenario A1 that the alternative climate change scenarios B1, C1, and D1 delivered.

[Figure 7]

[Figure 8]

In both cases, the European Community and Australia emerge as major producers, both increasing their relative allocation of production. In the case of the European Community, however, the effect does not hold for scenario A (when no conversions are allowed). While this last region did not favor from conversions to cropland, it did for conversions to pastureland. B1, C1, and D1 scenario runs reported that about 13.4, 1.1 and 1.4 million hectares of forestland were converted into pastureland in this region, respectively.

4. 2 World Prices

Figure 10 shows the changes in prices (from 1990) that resulted in the A and A1 scenario runs. Prices for agricultural commodities increase notoriously due to demand increases driven by population growth to the year 2100 alone (with no climate change altering the productivity of the system) when no forestland conversions are allowed (i.e., under scenario A1). Changes in world prices reflect changes in payments to intermediate inputs and factors of production, including scarcity rents. The dramatic increase in prices reflects increases in scarcity rents embodied in the commodity prices that result from agricultural land – particularly croplands – becoming increasingly scarce. Particularly strong are the increases in the prices of wheat and vegetables, fruits and nuts that the model predicts, with increases in the magnitude of 400 %.

[Figure 9]

Not surprisingly, when forestland conversions are allowed to take place, the pressure on agricultural land – particularly croplands - is relieved, and scarcity rents associated to agricultural land decreases dramatically, reducing the extent of the impact on prices. Price increases in wheat under scenario A1 drops to around 4% and prices of the vegetable, fruits and nuts category even decreases from the year 1990. Forestland conversion emerges as a very powerful mechanism of overcoming land scarcity and decreases in households' food access associated with agricultural price increases – so much that allowing for forestland conversions in the B1, C1 and D1 scenario runs world prices remained at the same level than in the A1 scenario (that is, a scenario without climate change effects), meaning that such conversions compensated the global productivity losses associates with the new climatic conditions.

5. Summary and Discussion

Using an extended version of the World Trade Model with Climate-Sensitive Land (WTMCL) modeling framework introduced by Julia' and Duchin (2007) we evaluate a set of scenarios entailing different combinations of climatic conditions and forestland conversions that may prevail in by the year 2100. We focus on the likelihood of agricultural commodity demand – driven by increases in population - being satisfied, and on the plausible changes in forestland conversions and prices that global adaptations to new climatic conditions and demand pressures may entail. The WTMCL framework allowed for trade adjustments consistent with changes in comparative advantage in response to the aforementioned impacts take place. Increases in food demand expanded production specialization in regions with lower comparative costs of production, and changes in land endowments associated with climatic conditions (and related changes in production potential) generated new patterns of regional specialization of production than the ones prevailing in the reference scenario of 1990. Adjustments entailed changes in the mix of agricultural products and the area devoted to agriculture – two of the major mechanisms of adaptation highlighted in the literature.

Our results suggest that global trade as a single mechanism of adjustment to the impacts of climate change will not suffice to compensate for productivity losses associated with the changing climatic conditions. Factor constraints – primarily croplands constraints - raise concerns about the long-run sustainability of this form of adaptation for the 100 years ahead. Climate change clearly increased the magnitude of agricultural land needed to satisfy the same demand requirements as in a world without changes (from 1990) in climate. This observation confirms the one suggested by Julia' and Duchin (2007): the requirements for agricultural commodities can be expected to increase substantially in the future due to population growth, compounding the stress due to climate change and jeopardizing the fulfillment of global agricultural demand.

Forestland conversions to croplands and to a lesser extent to pasturelands emerged as a powerful additional mechanism for overcoming reductions in global productivity of crops associated with climate change. While the demand for agricultural commodities projected to the year 2100 was attainable without the need of forestland conversions to agricultural land for 1990 climatic conditions, it became unattainable for conditions projected by three major General Circulation model predictions. This result is in accordance with scientific assessments, which point to climate change as a growing threat to agricultural yields and food security, more so than population growth. Recent droughts and floods in the Horn of Africa, Russia, Pakistan, and Australia – and their effects in food production and prices – are a reflection of the fact. (Science, 2012).

Forestland conversions allowed to overcome the infeasibility of all climate change scenarios; conversions required to satisfy projected agricultural demand vectors were in the magnitude of ¼ of current forestlands. Latin American forests (Amazonian forests) emerged as the region with the greatest advantage for forestland conversions. This result raises concerns due to the many ecosystem services that forest – particular tropical forest – provide as carbon sinks and as stabilizers of the global climate. Reducing atmospheric carbon emissions from reductions in tropical deforestation is at present considered a cost-effective option for mitigating climate change. However, the forces associated with tropical forest loss are uncertain, and this study concludes that forces and incentives for deforestation are likely to be considerably strong due to the pressures of feeding a global population and the adverse effects of climate change on agricultural productivity. DeFries et al. (2010) empirically showed, in support of this finding, a strong positive correlation between urban population growth and exports of agricultural products with forest loss (during the period 2000-2005), indicating the importance of urban-based and international demands for agricultural products as drivers of deforestation. Their findings and ours suggest that policies to reduce deforestation while meeting future demands of agricultural commodities need to focus on efforts to increase yields in non-forested lands rather than expanding production into forestlands.

This note of caution became even more relevant when evaluating the magnitude of price increases that fulfilling future demands for agricultural commodities may entail. When forestland conversion was not allowed, the model retrieved considerable increases in global agricultural prices; wheat prices increases, for example, were in the order of 400 percent (in reference to 1990 prices). Deforestation dramatically reduced the magnitude of such increases – (and even reduced prices of some commodities, such as oilseeds). While comparisons of price results between scenarios of climate change with and without forestland conversion was not possible due to the infeasibility of the later, rates of deforestation calculated by the model are not likely to take place, due to policy intervention and consideration of alternatives to the detrimental effects of deforestation. Constraints on available croplands especially, are likely to increase rents associated with their scarcity are likely to compound the effect on prices due to reductions and changes in crop suitability and productivity for different crops created by climate change on agricultural land. While in recent times, food insecurity has increased in several regions due to competing claims for land, water, labor, and capital leading to more pressure to improve production per unit of land, the price of food is unanimously cited as one of the leading determinants of food insecurity, as poor households' inability to secure food through markets and non-market channels due to increases in prices and/or decreases in income may limit food security even where food is globally abundant (Barrett, 2010). Giving this fact, we conclude that unless major improvements in agricultural productivity are implemented, along with population control and mitigation policies aimed at reducing the pressure that these two factors impose in the global system of agricultural production, food availability and access for future generations may be seriously jeopardized.

Assumptions made throughout the analysis limit its scope and need to be relaxed in further research. One such limitation is that on the economic side, the scenarios did not represent barriers to trade and so the solutions exhibited a higher degree of regional specialization than is plausible – and actually observed. A next step could consider embedding constraints imposed on production and trade. Regional resource constraints other than land, such as fresh water and availability of fossil fuels as well as the incorporation of policies aimed at reducing and/or limiting deforestation rates could also limit specialization and improve the plausibility of results.

References

Armington PS (1969) A theory of demand for products distinguished by place of production. IMF Staff Pap 16:159–178

Barrett, *C.B.*, Lentz, E.C. (*2010*). "Food Insecurity." In Robert Denemark et al. eds. The International Studies Compendium Project. Oxford: Wiley-Blackwell.

Beddington J.R., M. Asaduzzaman, M. E. Clark, A. Fernández Bremauntz, M. D. Guillou, D. J. B. Howlett, M. M. Jahn, E. Lin, T. Mamo, C. Negra, C. A. Nobre, R. J. Scholes, N. Van Bo, J. Wakhungu (2012). What Next for Agriculture After Durban? SCIENCE VOL 335, pp 289-290

Darwin RF, Tsigas M, Lewandrowski J, Raneses A (1995) World agriculture and climate change: economic adaptations. Agricultural Economic Report, no. 703, U.S. Department of Agriculture, Economic Research Service, Washington, District of Columbia

DeFries Ruth S., Thomas Rudel, Maria Uriarte & Matthew Hansen (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century *Nature Geoscience* 3, 178 - 181 Published online: 7 February 2010 | doi:10.1038/ngeo756

Duchin F (2005) A world trade model based on comparative advantage with m regions, n goods and k factors. Econ Syst Res 17(2):141–162

FAO. 2006. *World agriculture*: *towards 2030/2050*. Interim report. Prospects for food, nutrition, agriculture and major commodity groups.

Juliá R and Duchin, F (2007) World trade as the adjustment mechanism of agriculture to climate change *Climatic Change*, Vol. 82, No. 3-4: 393-409.

Randhir T, Hertel, TW (2000) Trade liberalization as a vehicle for adapting to global warming. Agric Resour Econ Rev 29(2):1–14

Reilly J, Hohmann N, Kane S (1994) Climate change and agricultural trade: who benefits, who loses. Glob Environ Change 4(1):24–36

Tsigas ME, Frisvold GV, Kuhn B (1996) Global climate change and agriculture. In: Hertel TW (ed) Global trade analysis: modeling and applications. Cambridge University Press, Cambridge, Massachusetts

United Nations (2004). World Population to 2300. Department of Economic and Social Affairs, Population Division. Working Paper No. ST/ESA/SER.A/236 New York.

Winters P, Murgai R, de Janvry A, Sadoulet E, Frisvold G (1999) Climate change and agriculture: effects on developing countries. In: Frisvold G, Kuhn B (eds) Global environmental change and agriculture. Edward Elgar, Cheltenham

TABLES

Table 1: Main characteristics of land-class categories

Land-class type	Length of growing season (days)	Soil temperature above 5 °C (days)	Principal crops and cropping pattern
1	0–100	<125	Sparse forage for rough grazing
2	0–100	>125	Millets, pulses, sparse forage for rough grazing
3	101–165	>125	Short-season grains; forage: one crop per year
4	166–250	>125	Maize: some double cropping possible. Cotton and rice: double cropping
5	251–300	>125	Cotton and rice: double cropping Common
6	301–365	>125	Rubber and sugarcane: double-cropping common

Source: Darwin et al., 1995

Table 2: Scenarios analyzed in the study

Scenario	Population (Reference Year)	Climatic Conditions	Forestland Conversion
1990	1990	1990 Climate	No forestland conversions allowed
A	2100 forecast	No climate change (Climate remains as in 1990)	No forestland conversions allowed
A1	2100 forecast	No climate change Assumed (climate remains as in 1990)	Forestland conversions allowed
B	2100 forecast	Climate change: GISS scenario	No forestland conversions allowed
B1	2100 forecast	Climate change: GISS Scenario	Forestland conversions allowed
C	2100 forecast	Climate change: UKMO Scenario	No forestland conversions allowed
C1	2100 forecast	Climate change: UKMO Scenario	Forestland conversions allowed
D	2100 forecast	Climate change: GFDL Scenario	No forestland conversions allowed
D1	2100 forecast	Climate change: GFDL Scenario	Forestland conversions allowed

Note: Climate change scenarios are the ones generated by the general circulation models of the the Goddard Institute for Space Studies (GISS), United KingdomMeteorological Office (UKMO) and the Geophysical Fluid Dynamics Laboratory (GFDL).
.

Table 3: Scenario feasibility and value of objective function

Scenario	Feasibility	Global Costs of Production (% Change from 1990 values)
A	Feasible	61.4
A1	Feasible	58.1
B	Unfeasible	n/a
B1	Feasible	58.2
C	Unfeasible	n/a
C1	Feasible	58.0
D	Unfeasible	n/a
D1	Feasible	58.1

Source: Own computations

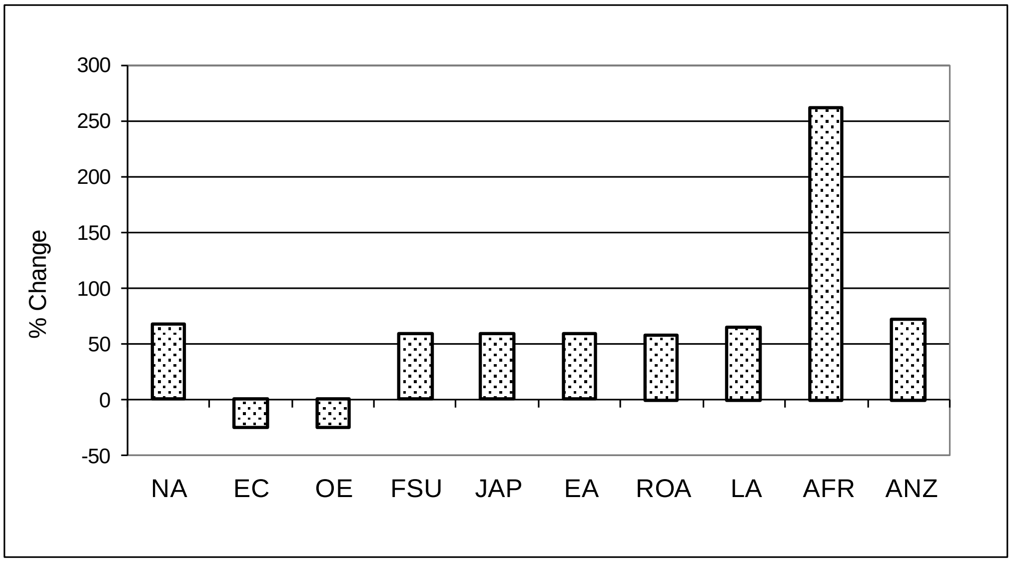
Table 4: Forestland conversions reported for all feasible scenario runs

Scenario	Forestland Converted to Cropland (Millions of Hectares)	Forestland Converted to Pasturelands (Millions of Hectares)	Total Forestlands Converted (Millions of Hectares)
A1	932.79	0.01	932.81
B1	1109.27	13.68	1122.95
C1	1097.05	1.18	1098.23
D1	1058.98	1.17	1060.16

Source: Own computations

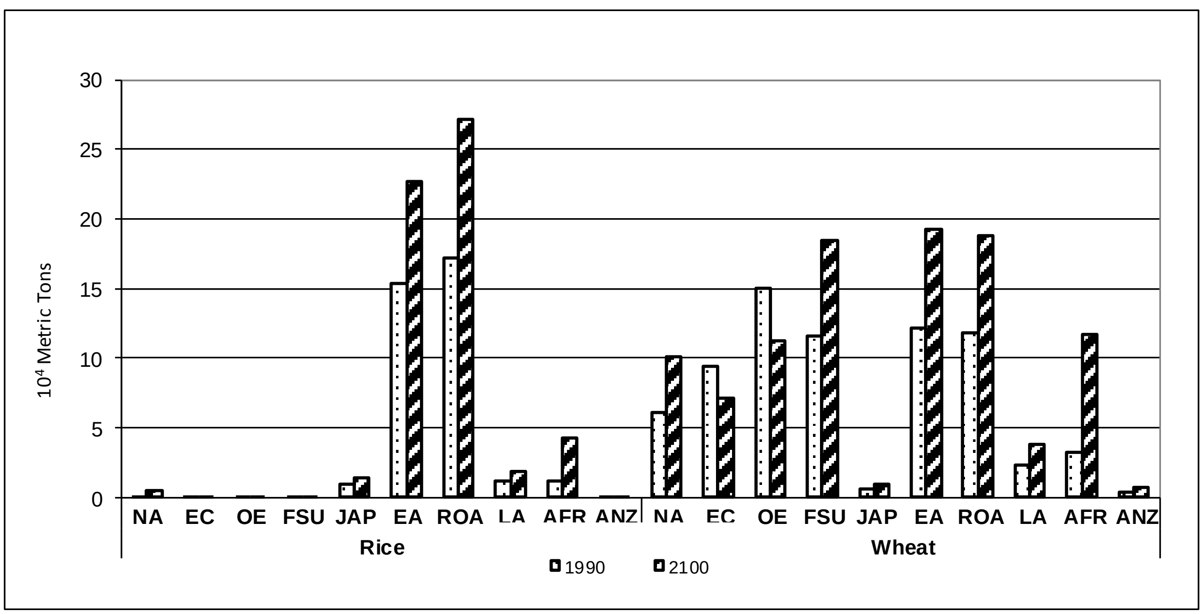
FIGURES

Figure 1: Population Change Estimates (1990-2100) Used to Increase Final Demand Vectors, by Region



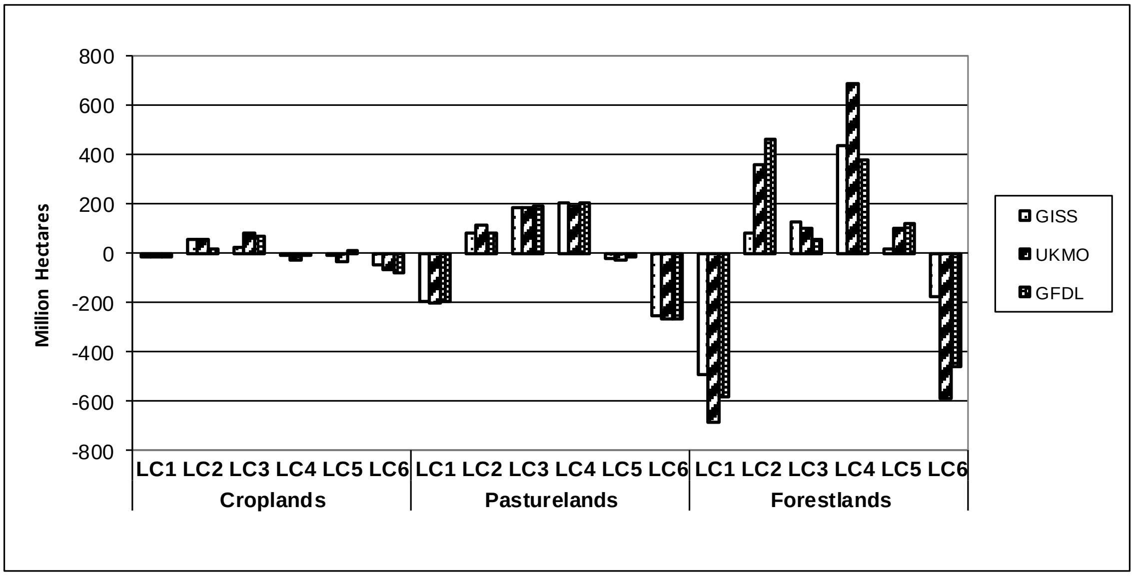
Source: UN, Population Division

Figure 2: Actual and Estimated Demand for Rice and Wheat for the Years 1990 and 2100, Respectively, by Region



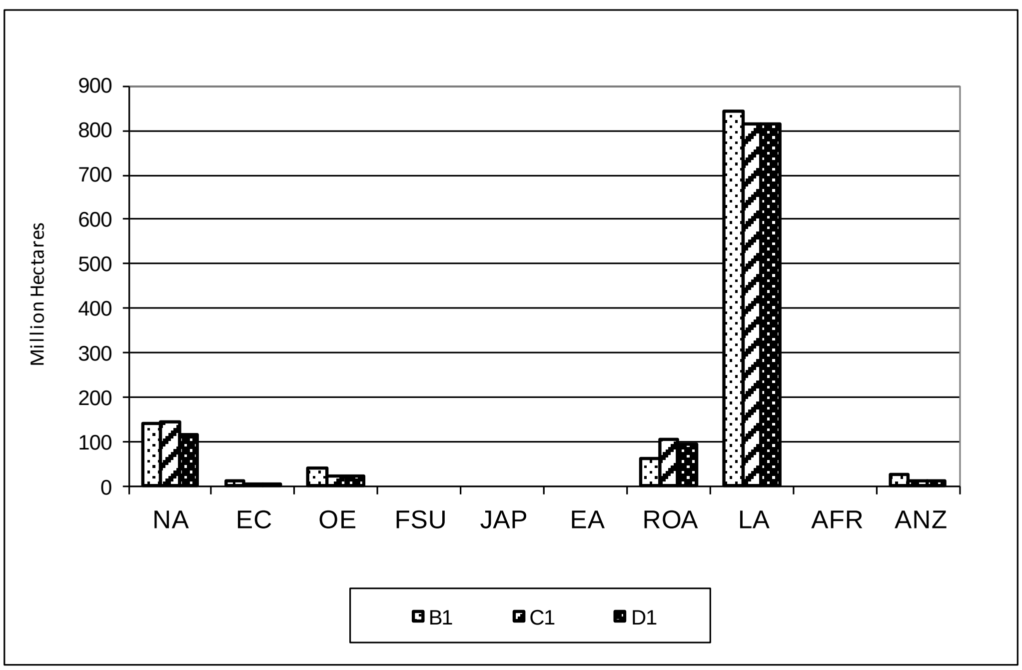
Source: FAO, Statistical Division and own computations

Figure 3: Changes in Global Land Resources by Use Type, Land-Class and Climate Change Scenario



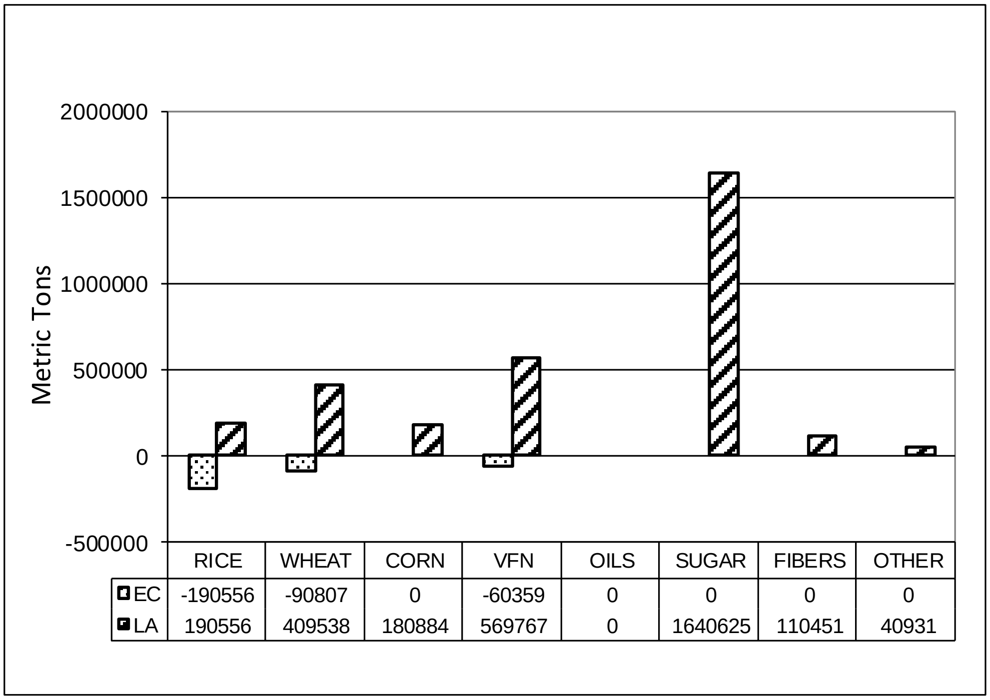
Source: Darwin et al., 1995
Note: Climate change scenarios are the ones generated by the general circulation models of the Goddard Institute for Space Studies (GISS), United Kingdom Meteorological Office (UKMO) and the Geophysical Fluid Dynamics Laboratory (GFDL).

Figure 4: Forestland Conversions to Cropland by Region, Resulting from Three Model Scenario Runs



Source: Own computations

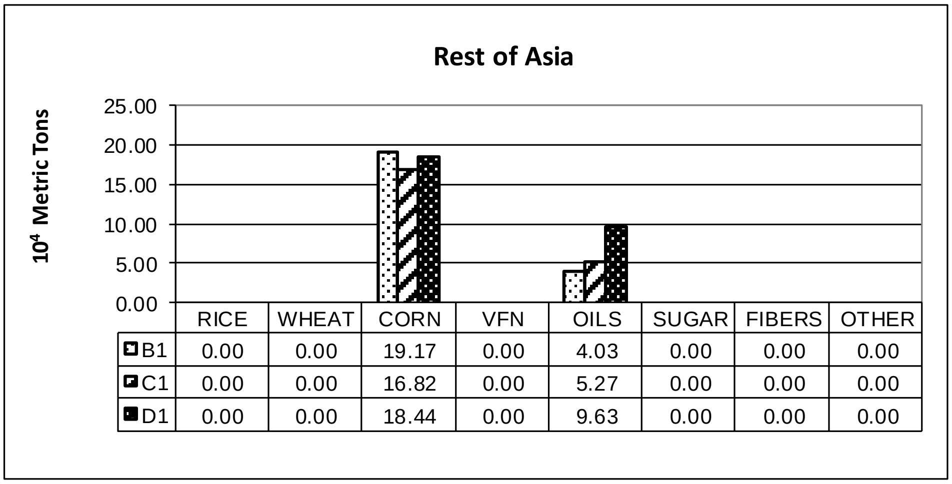
Figure 5: Changes in Crop Production and Specialization in the European Community (EC) and Latin America (LA) Resulting from Scenario A1 Run (Changes from Scenario A Run).



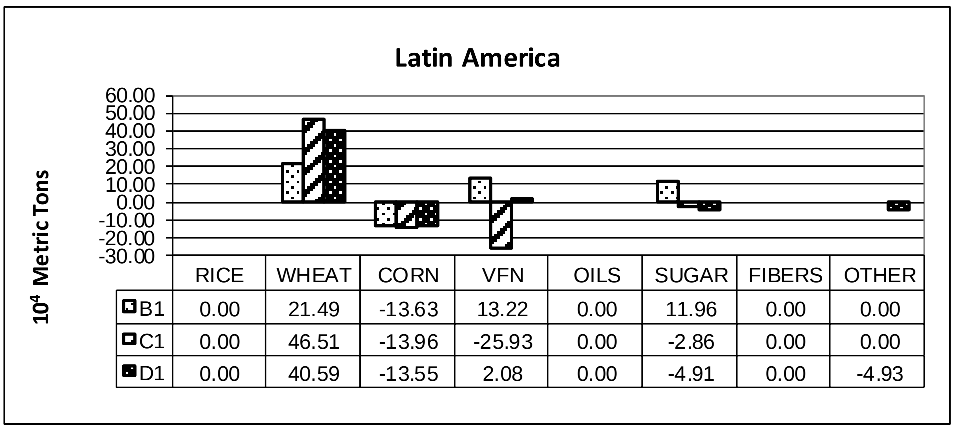
	RICE	WHEAT	CORN	VFN	OILS	SUGAR	FIBERS	OTHER
EC	-190556	-90807	0	-60359	0	0	0	0
LA	190556	409538	180884	569767	0	1640625	110451	40931

Source: Own Computations

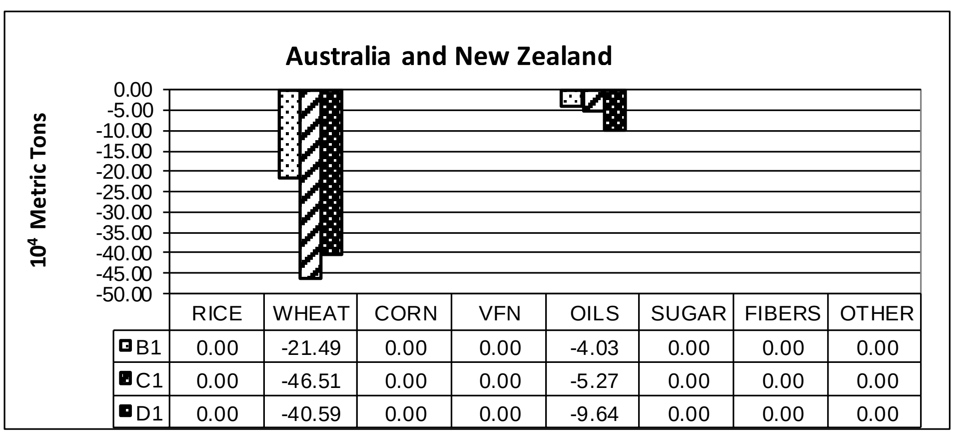
Figure 6: Changes (from Scenario A1 Results) in Crop Specialization under Three Model Scenario Runs: Selected Regions.



	RICE	WHEAT	CORN	VFN	OILS	SUGAR	FIBERS	OTHER
B1	0.00	0.00	19.17	0.00	4.03	0.00	0.00	0.00
C1	0.00	0.00	16.82	0.00	5.27	0.00	0.00	0.00
D1	0.00	0.00	18.44	0.00	9.63	0.00	0.00	0.00



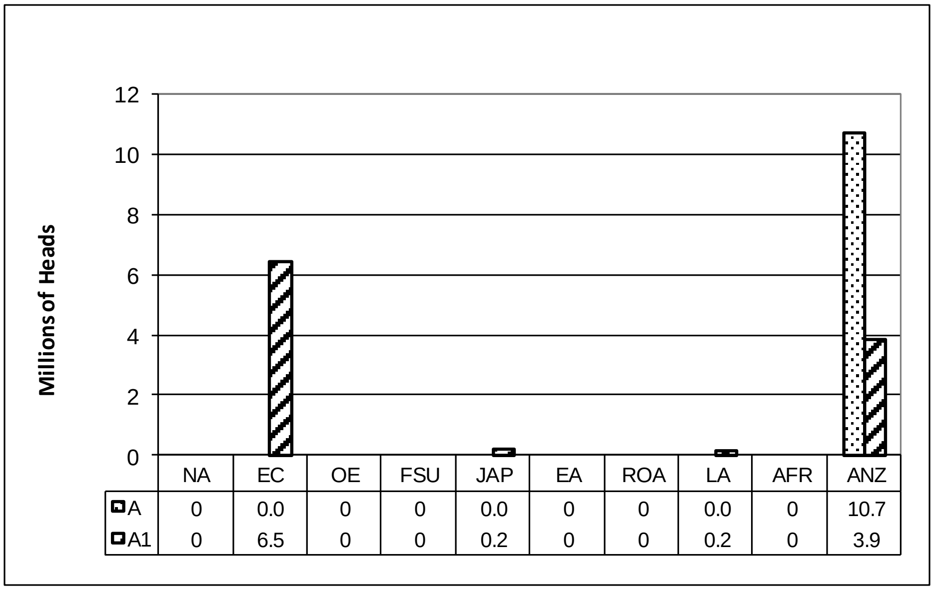
	RICE	WHEAT	CORN	VFN	OILS	SUGAR	FIBERS	OTHER
B1	0.00	21.49	-13.63	13.22	0.00	11.96	0.00	0.00
C1	0.00	46.51	-13.96	-25.93	0.00	-2.86	0.00	0.00
D1	0.00	40.59	-13.55	2.08	0.00	-4.91	0.00	-4.93



	RICE	WHEAT	CORN	VFN	OILS	SUGAR	FIBERS	OTHER
B1	0.00	-21.49	0.00	0.00	-4.03	0.00	0.00	0.00
C1	0.00	-46.51	0.00	0.00	-5.27	0.00	0.00	0.00
D1	0.00	-40.59	0.00	0.00	-9.64	0.00	0.00	0.00

Source: Own Computations

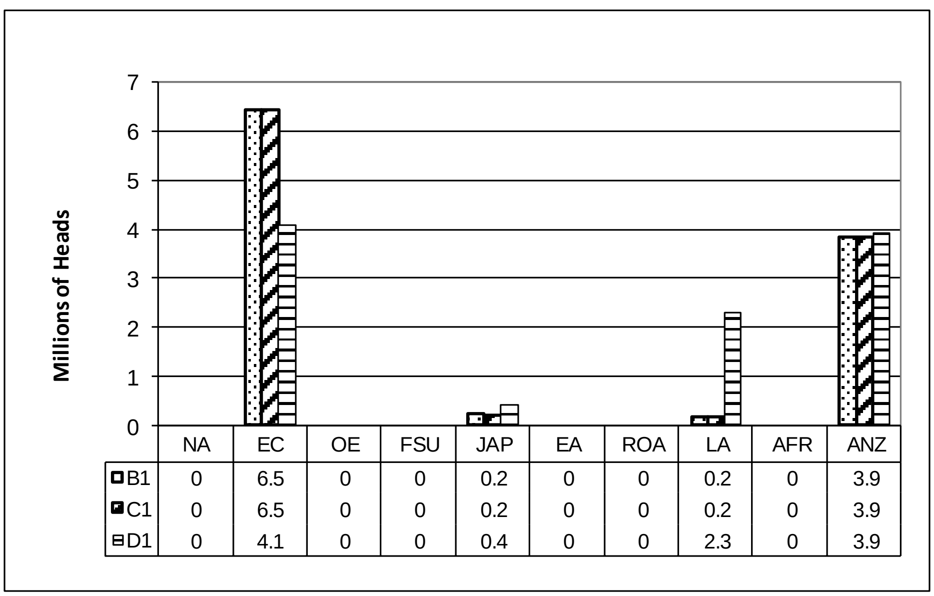
Figure 7: Changes in Livestock Specialization, by Region, Resulting from Scenario A1 Run (Changes are from Scenario A Run).



	NA	EC	OE	FSU	JAP	EA	ROA	LA	AFR	ANZ
A	0	0.0	0	0	0.0	0	0	0.0	0	10.7
A1	0	6.5	0	0	0.2	0	0	0.2	0	3.9

Source: Own computations

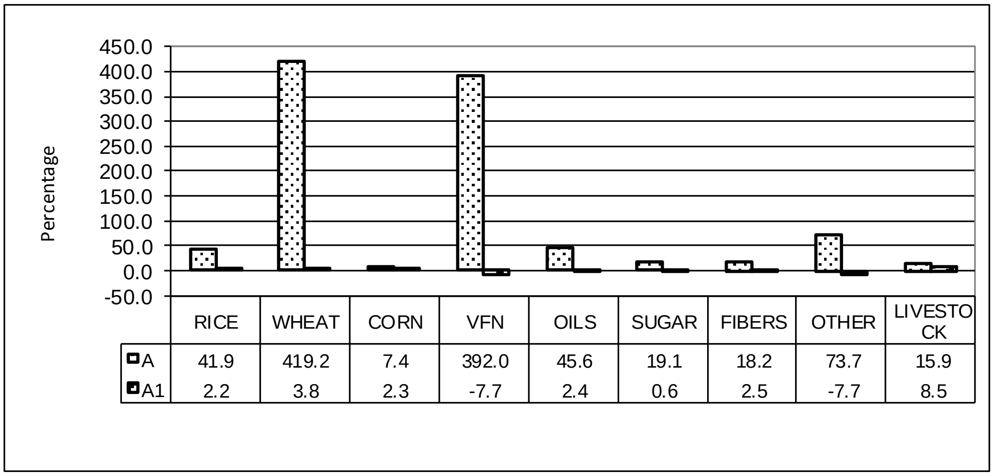
Figure 8: Changes (from Scenario A1 Results) in Livestock Specialization under Three Model Scenario Runs, by Region.



	NA	EC	OE	FSU	JAP	EA	ROA	LA	AFR	ANZ
B1	0	6.5	0	0	0.2	0	0	0.2	0	3.9
C1	0	6.5	0	0	0.2	0	0	0.2	0	3.9
D1	0	4.1	0	0	0.4	0	0	2.3	0	3.9

Source: Own computations

Figure 9: Percentage Change in World Prices of Agricultural Commodities, Obtained in the A and A1 Scenario Runs



Source: Own computations

---

[i] The studies cited above adopt the Armington (1969) assumption according to which producers and consumers distinguish commodities by country of origin, employing trade elasticities both to represent baseline sources of imports and to determine changes in sources of imports when regional production costs change. While the Armington assumption may yield production and trade effects of plausible magnitudes, it takes existing trade patterns, rather than ones based on comparative advantage, as its starting point and, in what amounts to a weak reflection of changes in comparative advantage, has countries continue to import from all sources even when regional prices change radically (Juliá and Duchin, 2007).

APPENDIX A
The World Trade Model With Climate Sensitive Land (WTMCL)

Primal:

$$\min_{x} \quad \sum_{i=1}^{m} \pi_i' F_i x_i$$

$$\text{s.t.} \quad \sum_{i=1}^{m} e_j'(I - A_i)x_i \geq \sum_{i=1}^{m} e_j' y_i \qquad \forall j \in T \qquad (1)$$

$$\sum_{i=1}^{m} \sum_{t=1}^{s} e_j'(I - A_i)x_{i,t} \geq \sum_{i=1}^{m} e_j' y_i \qquad \forall j \in \text{TL} \qquad (2)$$

$$e_j'(I - A_i)x_i = e_j' y_i \qquad \forall j \in NT; i = 1, \ldots, m \qquad (3)$$

$$F_i x_i \leq f_i \qquad i = 1, \ldots, m \qquad (4)$$

$$\sum_{\substack{j \in T \\ j \in NT}} e_z' \,\text{pnt}_i\, e_j'(I - A_i)x_i + \sum_{j \in \text{TL}} \sum_{t=1}^{s} e_z' \,\text{pnt}_i\, e_j'(I - A_i)x_i \leq \text{pnt}_i' y_i \qquad i = 1, \ldots, m \qquad (5)$$

$$x \geq 0$$

The dual is:

$$\max_{p0, \nu 0, w, r, \alpha} \quad p_0' \left(\sum_{j \in T} \sum_{i=1}^{m} e_j' y_i \right) + \nu_0' \left(\sum_{j \in \text{TL}} \sum_{i=1}^{m} e_j' y_i \right) + \sum_{j \in \text{NT}} \sum_{i=1}^{m} w_i e_j' y_i - \sum_{i=1}^{m} r_i' f_i - \sum_{i=1}^{m} \alpha_i \text{pnt}_i' y_i$$

$$\begin{aligned} \text{s.t.} \quad & \sum_{j \in T} (I - A_i)' e_j p_0 + \sum_{j \in \text{TL}} (I - A_i)' e_j \nu_0 + \sum_{j \in \text{NT}} (I - A_i)' e_j w_i \\ & - F_i' r_i - (I - A_i)' \text{pnt}_i \leq F_i' \pi_i \qquad i = 1, \ldots, m \\ & p_0, \nu_0, w, r, \alpha \geq 0 \qquad (6) \end{aligned}$$

where

x_i	Denotes n × 1 vector of commodity output in region i
p_0	Denotes g × 1 vector of world commodity prices for the traded commodities that do not use land
v_0	Denotes h × 1 vector of world commodity prices for the traded commodities that use land
w_i	Denotes q × 1 vector of regional commodity prices for the non-traded commodities in region i
r_i	Denotes k × 1 vector of scarcity rents in region i
a_i	Denotes scalar of benefits of trade in region i
y_i	Denotes [n - h (s – 1)x1 vector of commodity consumption in region i
π_i	Denotes k × 1 vector of factor prices in region i
	Denotes k × 1 vector of factor endowments in region i
pnt_i	Denotes [n - h (s – 1)x1 vector of pre-trade commodity prices in region i
e_j	Denotes column vector of required length with a 1 in the jth position and 0s everywhere else
e_z	Denotes [n - h (s – 1)x1 vector with a 1 in the zth place – corresponding to the pnt price of the commodity in the jth position – and 0s everywhere else
A_i	Denotes n × n matrix of inter-industry production coefficients in region i
F_i	Denotes k × n matrix of factor inputs per unit of output in region i
T	Denotes sub-set of the traded commodities that do not use land
TL	Denotes sub-set of the traded commodities that use land
NT	Denotes sub-set of the commodities to be non-traded
t	Denotes land-class assignment for the elements of the set TL
j	Denotes commodity
i	Denotes region